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Steinert

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(54) **MAXIMUM FILTER FLOW PREDICTOR**

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G01N 15/08	(2006.01)
B64C 27/14	(2006.01)
B01D 46/00	(2006.01)

(52) **U.S. Cl.**

CPC ***G01N 15/0826*** (2013.01); ***B64C 27/14*** (2013.01); *B01D 46/0086* (2013.01); *B01D 2279/60* (2013.01); *G01N 2015/084* (2013.01)

(58) **Field of Classification Search**

CPC G01N 15/0826; B01D 46/0086
USPC 702/127
See application file for complete search history.

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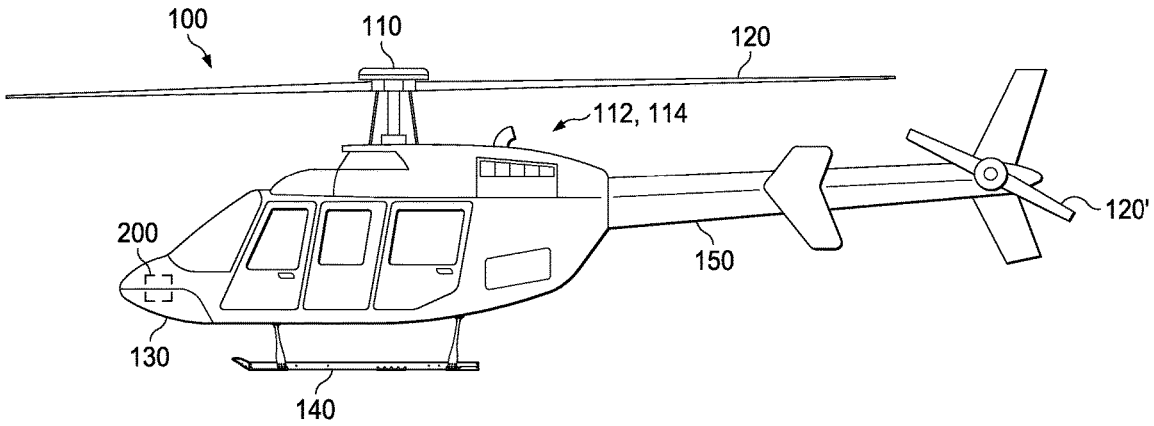
Primary Examiner — Anthony Ho

(57) **ABSTRACT**

In one example embodiment, a filter condition measurement device features an engine data repository, one or more sensor units, and a measurement unit. The measurement system is configured to identify a first flow value corresponding to a sensed engine power value from the engine data repository, determine a filter coefficient for the filter as a function of the first flow value and the sensed delta-pressure value; identify a second engine power value from the plurality of stored engine power values and a second flow value corresponding to the second engine power value; and determine a second delta-pressure value for the air filter as a function of the filter coefficient and the second flow value.

12 Claims, 6 Drawing Sheets



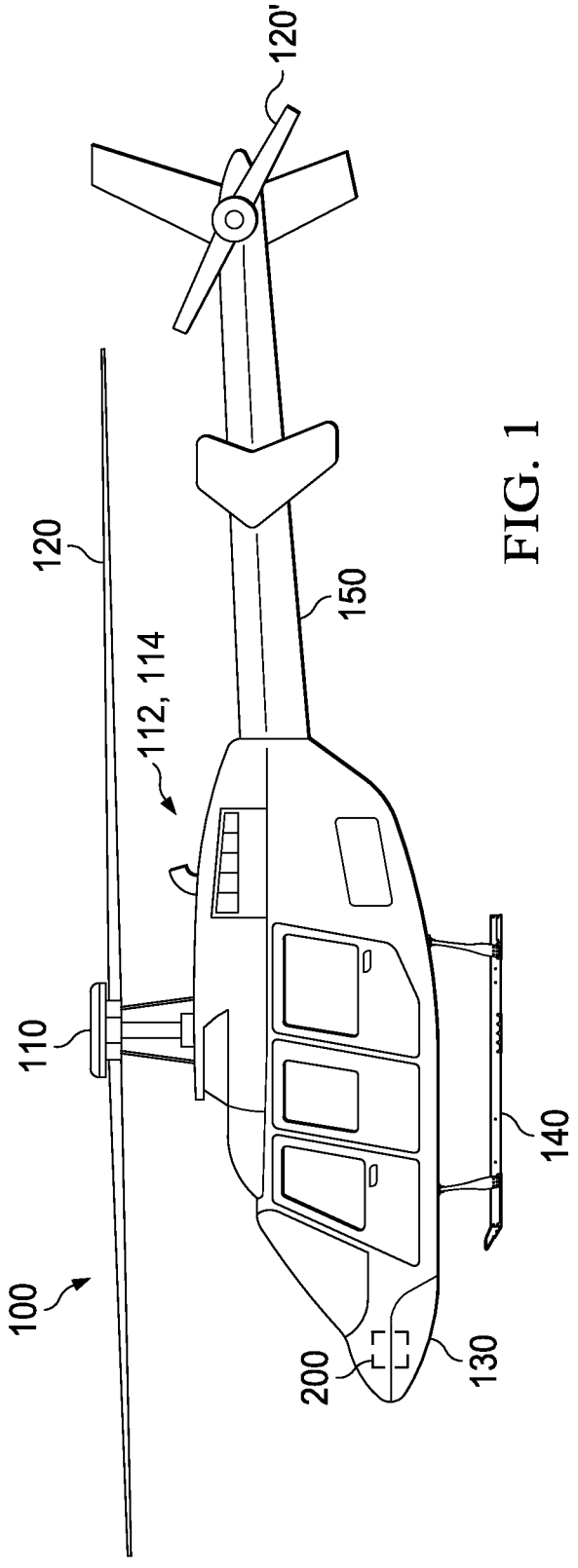


FIG. 1

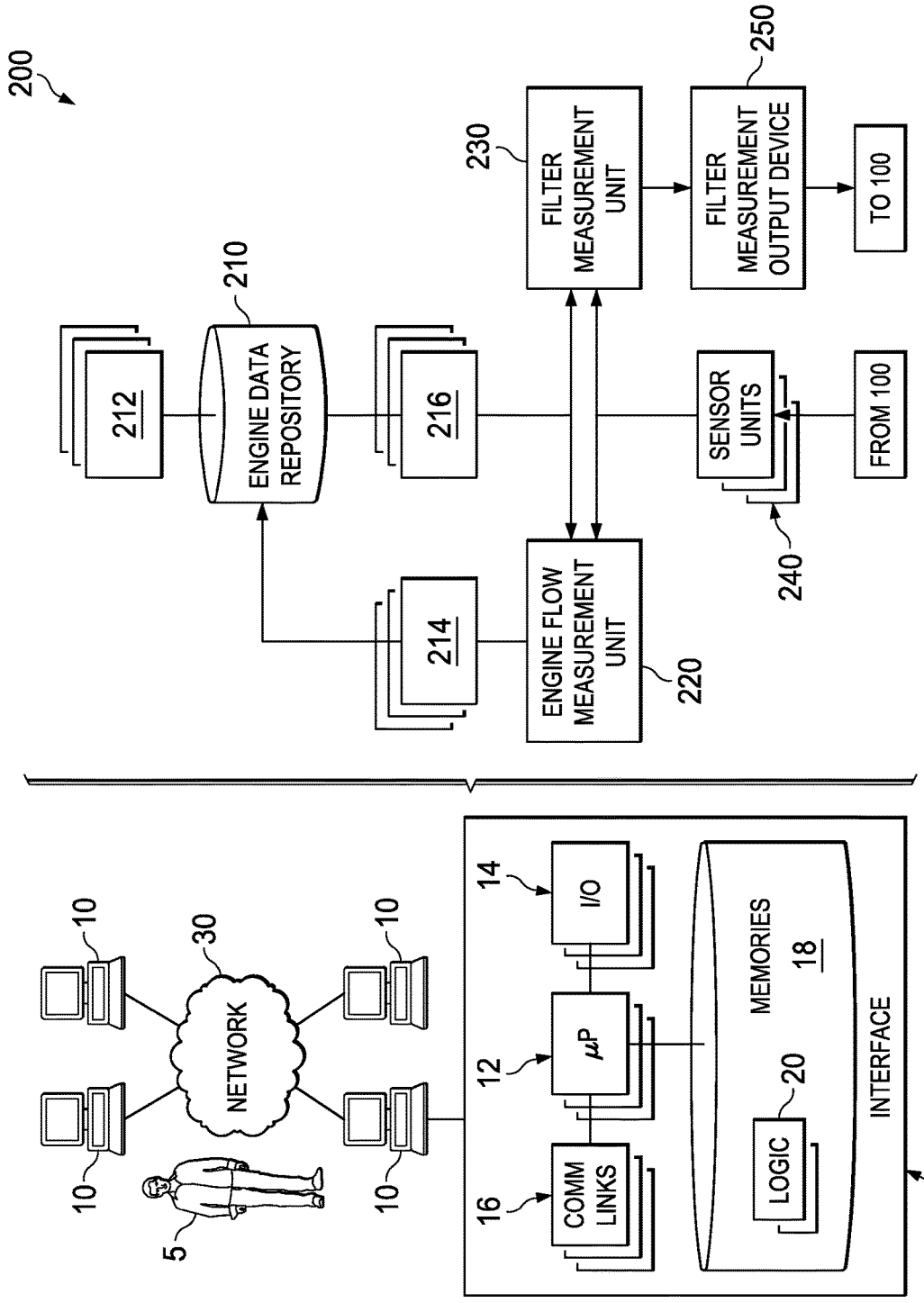

200
210
212
ENGINE DATA REPOSITORY
216
214
ENGINE FLOW MEASUREMENT UNIT
220
230
FILTER MEASUREMENT UNIT
250
FILTER MEASUREMENT OUTPUT DEVICE
TO 100
SENSOR UNITS
FROM 100
240
10
30
NETWORK
5
14
I/O
12
μP
16
COMM LINKS
MEMORIES
18
LOGIC
20
INTERFACE

FIG. 2

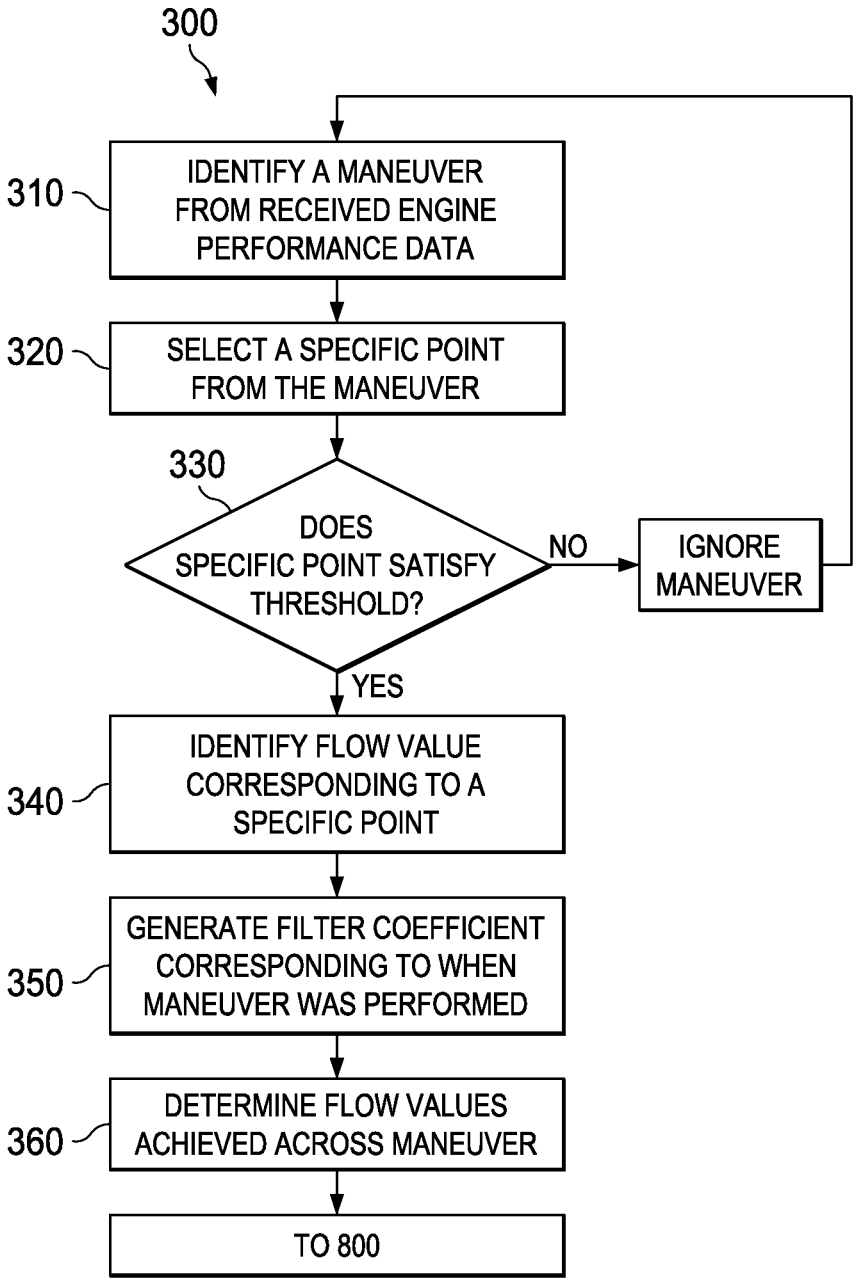

300
310
IDENTIFY A MANEUVER FROM RECEIVED ENGINE PERFORMANCE DATA
320
SELECT A SPECIFIC POINT FROM THE MANEUVER
330
DOES SPECIFIC POINT SATISFY THRESHOLD?
NO
IGNORE MANEUVER
YES
340
IDENTIFY FLOW VALUE CORRESPONDING TO A SPECIFIC POINT
350
GENERATE FILTER COEFFICIENT CORRESPONDING TO WHEN MANEUVER WAS PERFORMED
360
DETERMINE FLOW VALUES ACHIEVED ACROSS MANEUVER
TO 800

FIG. 3

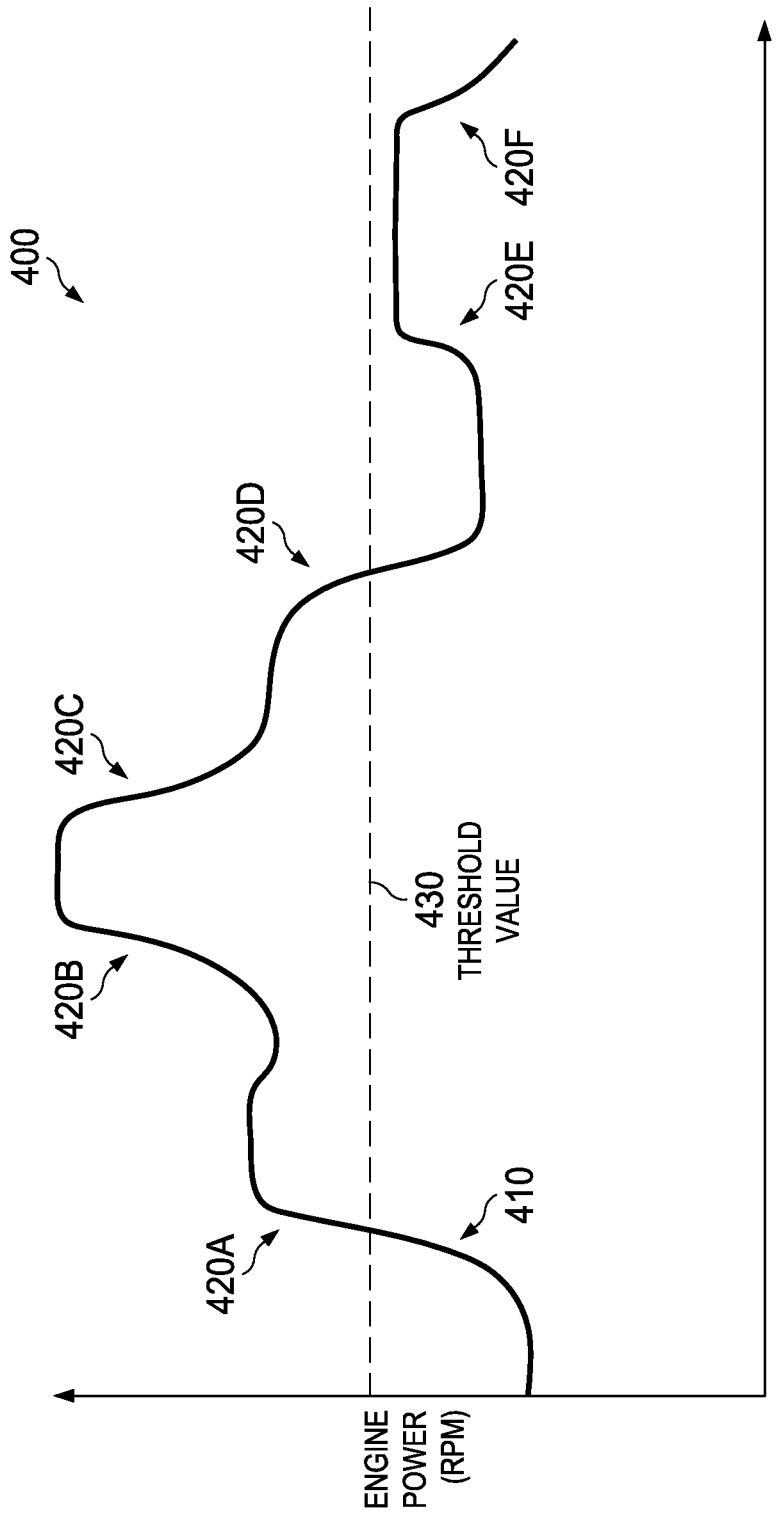

400
420A
420B
420C
420D
420E
420F
410
430
THRESHOLD
VALUE
ENGINE
POWER
(RPM)
TIME (t)

FIG. 4

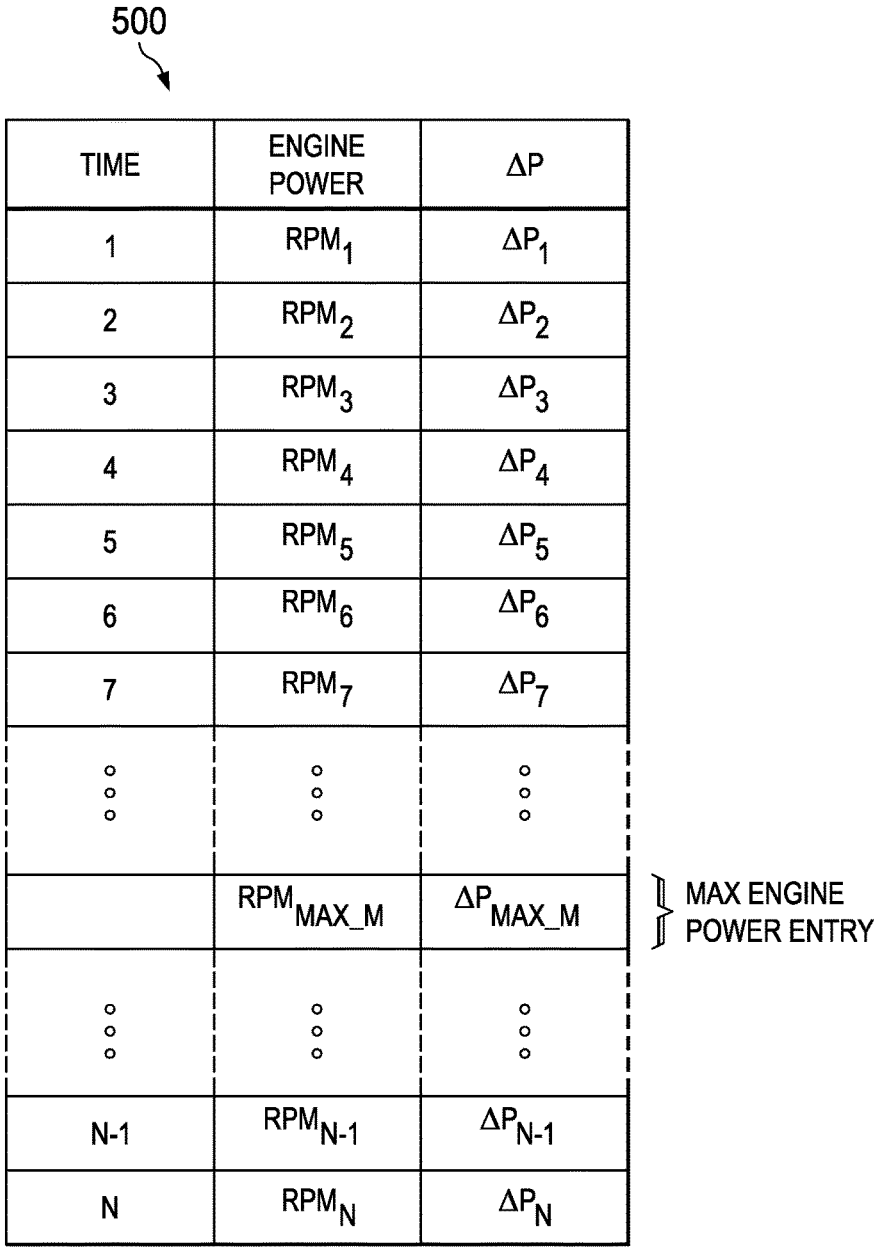

500
TIME
ENGINE POWER
ΔP
1
RPM1
ΔP1
2
RPM2
ΔP2
3
RPM3
ΔP3
4
RPM4
ΔP4
5
RPM5
ΔP5
6
RPM6
ΔP6
7
RPM7
ΔP7
RPMMAX_M
ΔPMAX_M
MAX ENGINE POWER ENTRY
N-1
RPMN-1
ΔPN-1
N
RPMN
ΔPN

FIG. 5

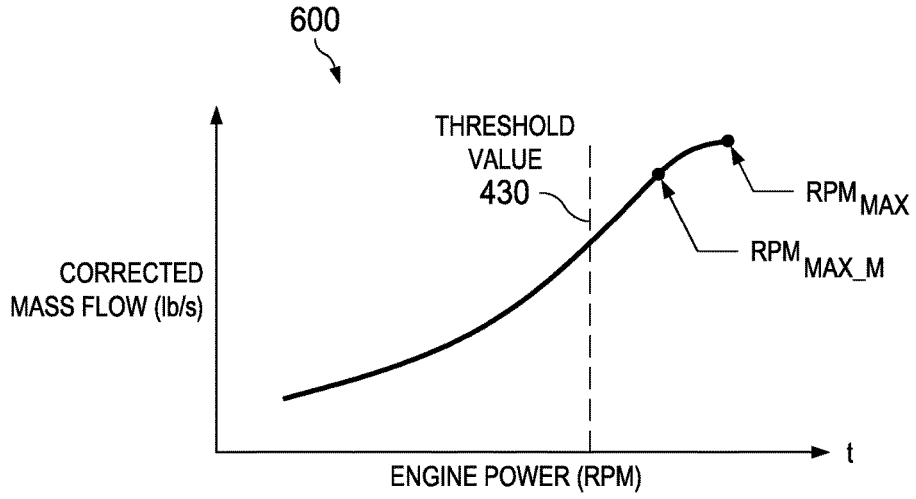


FIG. 6

700

ENGINE POWER	MASS FLOW
RPM_1	Q_1
RPM_2	Q_2
RPM_3	Q_3
RPM_4	Q_4
RPM_5	Q_5
RPM_6	Q_6
RPM_7	Q_7
⋮	⋮
RPM_{N-1}	Q_{N-1}
RPM_N	Q_N

FIG. 7

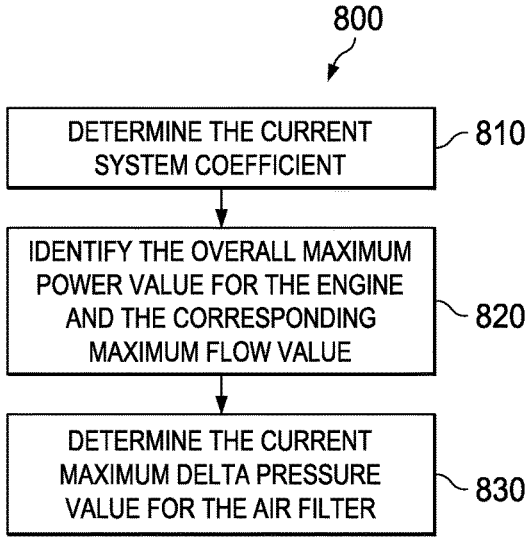


FIG. 8

MAXIMUM FILTER FLOW PREDICTOR

GOVERNMENT RIGHTS

At least some of the subject matter of this application may have been made with government support under contract number N00019-12-G-0006 and delivery order number 0054. The government may have certain rights in the invention.

TECHNICAL FIELD

This invention relates generally to aircraft health, and more particularly, to a maximum filter flow predictor.

BACKGROUND

One example of an aircraft is a rotorcraft. A rotorcraft may include one or more rotor systems. One example of a rotorcraft rotor system is a main rotor system. A main rotor system may generate aerodynamic lift to support the weight of the rotorcraft in flight and thrust to counteract aerodynamic drag and move the rotorcraft in forward flight. Another example of a rotorcraft rotor system is a tail rotor system. A tail rotor system may generate thrust in the same direction as the main rotor system's rotation to counter the torque effect created by the main rotor system.

Rotorcraft may be powered by an engine. Air filters may be provided to prevent unwanted materials from entering the engine.

SUMMARY

Particular embodiments of the present disclosure may provide one or more technical advantages. A technical advantage of one embodiment may include the capability to accurately predict how a degraded engine air filter will perform across a range of engine power levels during operation of the engine air filter. A technical advantage of one embodiment may include the capability to learn performance characteristics of a specific, unique engine. A technical advantage of one embodiment may include the capability to improve vehicle performance, pilot safety, and engine lifespan.

Certain embodiments of the present disclosure may include some, all, or none of the above advantages. One or more other technical advantages may be readily apparent to those skilled in the art from the figures, descriptions, and claims included herein.

BRIEF DESCRIPTION OF THE DRAWINGS

To provide a more complete understanding of the present invention and the features and advantages thereof, reference is made to the following description taken in conjunction with the accompanying drawings, in which:

FIG. **1** shows a rotorcraft according to one example embodiment;

FIG. **2** shows a measurement system that may be installed on or communicate with a vehicle such as the rotorcraft of FIG. **1** according to one example embodiment;

FIG. **3** shows a method for measuring flow values across a range of engine power values that may be executed at least partially by a system such as the system of FIG. **2** according to one example embodiment;

FIG. **4** shows an example graph charting two types of received engine performance data: engine power (rpm) over time (t);

FIG. **5** shows an example table of delta-pressure values corresponding to the engine power levels and times of the graph of FIG. **4**;

FIG. **6** shows an example chart of engine power values and corrected mass flow values contained within the processed engine data of system according to one example embodiment;

FIG. **7** shows an example table of flow values and corresponding engine power values determined using the method of FIG. **3** according to one example embodiment; and

FIG. **8** shows a method for determining the current delta-pressure value corresponding to the overall maximum power level for the engine that may be executed at least partially by a system such as the system of FIG. **2** according to one example embodiment.

DETAILED DESCRIPTION OF THE DRAWINGS

FIG. **1** shows a rotorcraft **100** according to one example embodiment. Rotorcraft **100** features a rotor system **110**, blades **120**, a fuselage **130**, a landing gear **140**, and an empennage **150**. Rotor system **110** may rotate blades **120**. Rotor system **110** may include a control system for selectively controlling the pitch of each blade **120** in order to selectively control direction, thrust, and lift of rotorcraft **100**. Fuselage **130** represents the body of rotorcraft **100** and may be coupled to rotor system **110** such that rotor system **110** and blades **120** may move fuselage **130** through the air. Landing gear **140** supports rotorcraft **100** when rotorcraft **100** is landing and/or when rotorcraft **100** is at rest on the ground. Empennage **150** represents the tail section of the aircraft and features components of a rotor system **110** and blades **120'**. Blades **120'** may provide thrust in the same direction as the rotation of blades **120** so as to counter the torque effect created by rotor system **110** and blades **120**. Teachings of certain embodiments relating to rotor systems described herein may apply to rotor system **110** and/or other rotor systems, such as other tilt rotor and helicopter rotor systems. It should also be appreciated that teachings regarding rotorcraft **100** may apply to aircraft and vehicles other than rotorcraft, such as airplanes and unmanned aircraft, to name a few examples.

Vehicles such as rotorcraft **100** may be powered by an engine. An air filter may be provided to prevent unwanted materials from entering the engine. In the example of FIG. **1**, rotorcraft **100** is equipped with at least one engine **112** and at least one air filter **114**.

Over time, the operating condition of the air filter may deteriorate. For example, certain types of air filters may become increasingly clogged such that the air filter allows less and less air through.

Operation of an engine air filter may be expressed by the following formula:

$$\Delta P = K_T Q^2,$$

wherein ΔP represents the change in pressure across the filter, K_T is a system resistance coefficient, and Q is the volumetric flow. The pressure change, ΔP, may be directly measured using a variety of pressure sensors. In some circumstances, Q may be represented by mass flow if incompressible fluid flow is assumed. The mass flow may be determined based on a relationship between mass flow and engine power, as will be explained in greater detail below.

The system resistance coefficient, K_T, may represent the operating condition of the air filter at a particular moment in time. Thus, the value of the system resistance coefficient may change over time because the operating condition of the air filter may change over time. This system resistance coefficient may not, however, change with volumetric flow or engine power; therefore, the resistance coefficient may be presumed fixed at a specific moment in time.

In order for a vehicle such as rotorcraft **100** to operate properly, the air filter should be in sufficient condition so that pressure change across the filter, ΔP, can satisfy certain operating requirements. As seen in the equation above, a change in the system resistance coefficient, K_T, over time due to deterioration of the air filter may result in ΔP no longer satisfying the operating requirements.

The pressure change across the filter, ΔP, also varies as a function volumetric flow, Q. As stated above, the volumetric flow may be a function of engine power. As a result, situations may arise in which ΔP satisfies operating requirements when engine power is low but then fails to satisfy the operating requirements when engine power increases.

Such a situation may arise, for example, during operation of a vehicle such as rotorcraft **100**. Consider rotorcraft **100** flying under normal operating conditions with an air filter that has deteriorated over time. In this scenario, the deteriorated condition of the air filter may not be apparent because the pressure change across the filter, ΔP, satisfies the minimum operating requirements.

But now consider what happens if rotorcraft **100** loses power in one of its two engines. In this situation, known as a one-engine-inoperative (OEI) flight condition, the pilot may increase power in the still-operative second engine to compensate for the loss of power in the first engine. By increasing engine power, however, volumetric flow, Q, also increases. As a result, the pressure change across the filter, ΔP, may no longer satisfy the minimum operating requirements.

Piloting rotorcraft **100** during OEI flight is a poor time to learn that the air filter is clogged and can no longer support minimum operating requirements. When confronted with an OEP flight condition, the pilot may be "task saturated" and be too busy to perform additional actions.

In addition to making a dangerous situation worse for the pilot and crew, failing to predict when the air filter will no longer be able to support minimum operating requirements can result in serious damage to the aircraft. Returning to the OEI example, the pilot may have to bypass the air filter in order to allow enough air into the engine to satisfy operating requirements. Bypassing the air filter, however, may allow an assortment of particulates and debris into the engine, causing serious damage to the engine. In some situations, the damage to the engine may be so significant that the engine must be retired early. This may force the vehicle maintainer to repair or replace a very expensive part (an engine) because a relatively-inexpensive part (a filter) failed.

Thus, the pressure change across the filter, ΔP, should satisfy operating requirements across a range of flow values and engine power values. Accordingly, teachings of certain embodiments recognize the capability to predict what the pressure change across the filter, ΔP, across a range of engine power values based on the current operating condition of the air filter (as expressed by system resistance coefficient, K_T). In particular, teachings of certain embodiments recognize the capability to predict what the pressure change across the filter will be if the engine is throttled to maximum power.

The accuracy of such predictions, however, is limited by the accuracy of the input values. In particular, inaccurate values for the volumetric flow variable, Q, may result in inaccurate assessments of air filter health.

As stated above, a relationship may exist between volumetric flow, Q, and engine power. An engine manufacturer may provide estimates of this relationship based on their testing data. These estimates, however, may not be sufficiently accurate, especially at low engine power. In particular, estimates for how a model of engine will perform may not account for the uniqueness of each particular engine and the uniqueness of the operating environment of each particular engine (e.g., what vehicle the particular engine is installed in and where that vehicle operates).

Accordingly, teachings of certain embodiments recognize the capability to collect volumetric flow data unique to a particular engine and then use this unique data to assess the condition of an air filter associated with that particular engine. In this manner, a measurement system may "learn" how an engine operates and then measure air filter health based on this learned information. Teachings of certain embodiments recognize that utilizing learned engine data may result in more accurate predictions regarding how an associated air filter will perform across a range of engine power settings, including a maximum engine power setting.

FIG. **2** shows a measurement system **200** according to one example embodiment. FIG. **2** shows a health and maintenance system **200** according to one example embodiment. In the example of FIG. **2**, system **200** features an engine data repository **210**, an engine flow measurement unit **220**, a filter measurement unit **230**, sensor units **240**, and a filter measurement output device **250**, which may be implemented by one or more computers **10** communicating across one or more networks **30** and accessible by a user **5**. Example of computer systems **10** may include, but are not limited to, a computer installed on-board an aircraft such as rotorcraft **100** (e.g., a flight control computer), a ground station computer, a maintenance computer, a data processing server, and an end-user computer. In various embodiments, elements of system **200** may be installed on-board an aircraft, off-board, or a combination of the two.

Users **5** may access system **200** through computer systems **10**. Users **5** may include any individual, group of individuals, entity, machine, and/or mechanism that interacts with computer systems **10**. Examples of users **5** include, but are not limited to, a maintenance person, pilot, engineer, technician, owner, operator, contractor, agent, and/or employee. Some of these terms may be used interchangeably throughout; for example, an owner may also be an operator. Generally, these terms should be construed to represent any party having a role associated with a vehicle such as rotorcraft **100** without the role being given a specific or narrow meaning.

Users **5** may be associated with an organization. An organization may include any social arrangement that pursues collective goals. One example of an organization is a business. A business is an organization designed to provide goods or services, or both, to consumers, governmental entities, and/or other businesses.

Computer system **10** may include processors **12**, input/output devices **14**, communications links **16**, and memory **18**. In other embodiments, computer system **10** may include more, less, or other components. Computer system may be operable to perform one or more operations of various embodiments. Although the embodiment shown provides one example of computer system **10** that may be used with other embodiments, such other embodiments may utilize computers other than computer system **10**. Additionally, embodiments may also employ multiple computer systems

10 or other computers networked together in one or more public and/or private computer networks, such as one or more networks **30**.

Processors **12** represent devices operable to execute logic contained within a medium. Examples of processor **12** include one or more microprocessors, one or more applications, and/or other logic. Computer system **10** may include one or multiple processors **12**.

Input/output devices **14** may include any device or interface operable to enable communication between computer system **10** and external components, including communication with a user or another system. Example input/output devices **14** may include, but are not limited to, a mouse, keyboard, display, and printer.

Network interfaces **16** are operable to facilitate communication between computer system **10** and another element of a network, such as other computer systems **10**. Network interfaces **16** may connect to any number and combination of wireline and/or wireless networks suitable for data transmission, including transmission of communications. Network interfaces **16** may, for example, communicate audio and/or video signals, messages, internet protocol packets, frame relay frames, asynchronous transfer mode cells, and/or other suitable data between network addresses. Network interfaces **16** connect to a computer network or a variety of other communicative platforms including, but not limited to, a public switched telephone network (PSTN); a public or private data network; one or more intranets; a local area network (LAN); a metropolitan area network (MAN); a wide area network (WAN); a wireline or wireless network; a local, regional, or global communication network; an optical network; a satellite network; a cellular network; an enterprise intranet; all or a portion of the Internet; other suitable network interfaces; or any combination of the preceding.

Memory **18** represents any suitable storage mechanism and may store any data for use by computer system **10**. Memory **18** may comprise one or more tangible, computer-readable, and/or computer-executable storage medium. Examples of memory **18** include computer memory (for example, Random Access Memory (RAM) or Read Only Memory (ROM)), mass storage media (for example, a hard disk), removable storage media (for example, a Compact Disk (CD) or a Digital Video Disk (DVD)), database and/or network storage (for example, a server), and/or other computer-readable medium.

In some embodiments, memory **18** stores logic **20**. Logic **20** facilitates operation of computer system **10**. Logic **20** may include hardware, software, and/or other logic. Logic **20** may be encoded in one or more tangible, non-transitory media and may perform operations when executed by a computer. Logic **20** may include a computer program, software, computer executable instructions, and/or instructions capable of being executed by computer system **10**. Example logic **20** may include any of the well-known OS2, UNIX, Mac-OS, Linux, and Windows Operating Systems or other operating systems. In particular embodiments, the operations of the embodiments may be performed by one or more computer readable media storing, embodied with, and/or encoded with a computer program and/or having a stored and/or an encoded computer program. Logic **20** may also be embedded within any other suitable medium without departing from the scope of the invention.

Various communications between computers **10** or components of computers **10** may occur across a network, such as network **30**. Network **30** may represent any number and combination of wireline and/or wireless networks suitable for data transmission. Network **30** may, for example, communicate internet protocol packets, frame relay frames, asynchronous transfer mode cells, and/or other suitable data between network addresses. Network **30** may include a public or private data network; one or more intranets; a local area network (LAN); a metropolitan area network (MAN); a wide area network (WAN); a wireline or wireless network; a local, regional, or global communication network; an optical network; a satellite network; a cellular network; an enterprise intranet; all or a portion of the Internet; other suitable communication links; or any combination of the preceding. Although the illustrated embodiment shows one network **30**, teachings of certain embodiments recognize that more or fewer networks may be used and that not all elements may communicate via a network. Teachings of certain embodiments also recognize that communications over a network is one example of a mechanism for communicating between parties, and any suitable mechanism may be used.

In the example of FIG. **2**, engine data repository **210** stores performance information associated with a particular engine. In the example embodiment of FIG. **2**, engine data repository **210** receives baseline engine data **212** from an outside source, such as from an engine manufacturer. This baseline engine data **212** may not be unique to a particular engine, but rather may be generic to a category of engines, such as a model of engines.

Engine data repository **210** may also store engine data that is unique to a particular engine. In the example of FIG. **2**, engine data repository **210** receives engine data updates **214** from engine flow measurement unit **220**. These engine data updates **214** may be unique to a particular engine.

Engine data repository **210** may also store and provide processed engine data **216**. Processed engine data **216** may be based on the baseline engine data **212** and/or the engine data updates **214** received by engine data repository **210**. For example, in one embodiment, processed engine data **216** may represent the combination of baseline engine data **212** and engine data updates **214**. In another example embodiments, processed engine data **216** includes all or some of engine data updates **214** but does not include all of the baseline engine data **212** because engine data updates **214** are presumed to be more accurate than baseline engine data **212** over certain data ranges.

Baseline engine data **212**, engine data updates **214**, and processed engine data **216** may represent a variety of different categories of data. In one example embodiment, baseline engine data **212**, engine data updates **214**, and processed engine data **216** includes engine power values and associated flow values (e.g., volumetric flow values or mass flow values). Engine power values may include any representation of engine power. In some example embodiments, engine power values may be expressed by a value such as revolutions-per-minute (rpms), which may have a relationship with engine power. In other embodiments, a metric other than rpms (such as engine torque) may be used. Although example embodiments described herein may appear to use terms such as "engine power" and "rpms" interchangeably, metrics other than rpms may be used when appropriate. Likewise, references to engine power may also include references to other metrics that are analogous or somehow related to engine power.

Engine flow measurement unit **220** measures engine flow unique to a particular engine and generates engine data updates **214**. In the example of FIG. **2**, engine flow measurement unit **220** receives processed engine data **216** and input from sensor units **240** and generates engine data

updates **214**. In some embodiments, engine data repository **210** and engine flow measurement unit **220** may operate in a continuously-iterative manner. For example, engine flow measurement unit **220** may receive processed engine data **216** and generate engine data updates **214**; engine data repository **210** may add the engine data updates **214** to existing engine data to yield new processed engine data **216**, which engine flow measurement unit **220** may utilize to generate new engine data updates **214**, and so forth.

In some embodiments, engine flow measurement unit **220** may utilize baseline engine data **212** instead of processed engine data **216**. Such may be the case, for example, if no processed engine data **216** exists yet. In this example, engine flow measurement unit **220** may start this iterative process using baseline engine data **212** and then may switch to using processed engine data **216** at a later time.

Filter measurement unit **230** measures aspects associated with the air filter, such as the air filter operating condition or the change in pressure across the air filter at different engine operating conditions. Filter measurement output device **250** receives measurements from filter measurement unit **230** and provides some sort of output. Examples of such an output may include, but are not limited to, an alert to the pilot that the air filter condition may be degraded or an alert to the maintenance crew that the air filter should be repaired or replaced.

Filter measurement unit **230** utilizes processed engine data **216** to measure aspects associated with the air filter. Teachings of certain embodiments recognize that using processed engine data **216** may lead to more accurate air filter measurements than using baseline engine data **212**.

In the example of FIG. **2**, engine flow measurement unit **220** and filter measurement unit **230** may perform various calculations using information from sensor units **240**. Sensor units **240** may represent any device capable of collecting information from a vehicle such as rotorcraft **100**. Examples of sensor units **240** may include sensors installed onboard the vehicle or devices in communication with sensors installed onboard the vehicle. Examples of information collected from the vehicle may include, but is not limited to, performance data such as delta-pressure values (ΔP) and associated engine power values (rpms).

FIG. **3** shows a method **300** for measuring flow values across a range of engine power values according to one example embodiment. In some embodiments, all or some of the steps of method **800** may be performed by the engine power measurement unit **220** of system **200**. References are made to FIGS. **4-7**, which illustrate various concepts utilized during the performance of method **300**.

At step **310** of method **300**, a maneuver is identified from received engine performance data. Examples of the received engine performance data may include, but is not limited to, performance data such as delta-pressure values (ΔP) and associated engine power values (rpms).

FIG. **4** shows an example graph **400** that charts two types of received engine performance data: engine power (rpm) over time (t). In this example, each received engine power value may also have a corresponding delta-pressure value (ΔP), such as shown in the example table **500** of FIG. **5**. In table **500**, each point in time (n) has a corresponding engine power level (RPM_n) and delta-pressure value (ΔP_n).

In the example graph **400** of FIG. **4**, an engine power history **410** is charted over time. In this example, maneuvers may be identified from engine power history **410**. For example, in FIG. **4**, six "power sweeps" **420***a*-**420***f* are identified. In this example, a power sweep may represent a significant change in engine power over a small period of time.

At step **320** of method **300**, a specific point is selected from identified maneuver. One example of selecting a specific point may include selecting a specific engine power value and corresponding specific delta-pressure value from the identified maneuver. Returning to the example of FIG. **4**, selecting a specific point from an identified maneuver may include selecting the highest engine power value from an identified power sweep, such as power sweeps **420***a*-**420***f*. Teachings of certain embodiments recognize that some engine data (such as data provided by engine manufacturers) may be more accurate at higher engine power levels, so selecting the highest engine power value from an identified power sweep at step **320** may lead to more accurate results. In the example table **500** of FIG. **5**, the maximum engine power value is expressed as RPM_{MAX_M} and the corresponding delta-pressure value is expressed as ΔP_{MAX_M}.

Not only may engine data (such as data provided by engine manufacturers) be more accurate at higher engine power levels, but there may a threshold above which engine power values are presumed accurate but below which engine power values are not presumed accurate. In the example of FIG. **4**, an example threshold engine value is shown as threshold value **430**.

At step **330** of method **300**, the selected specific point is compared to a threshold value, such as a threshold engine power level value. If the selected specific point satisfies the threshold value, then the method proceeds to step **340**; if not, the identified maneuver may be disregarded, and a new maneuver may be identified.

Returning to the example of FIG. **4**, the selected point may satisfy the threshold value if, for example, the highest engine power value in a power sweep (RPM_{MAX_M}) is higher than threshold engine power value **430**. In the example of FIG. **3**, four power sweeps (**420***a*, **420***b*, **420***c*, and **420***d*) satisfy the threshold, but two power sweeps (**420***e* and **420***f*) do not have engine power values high enough to satisfy the threshold.

At step **340** of method **300**, a flow value (Q) is identified corresponding to the specific point. In one example embodiment, the identified flow value (Q) is the Q_{MAX_M} corresponding to RPM_{MAX_M}. The value of Q_{MAX_M} corresponding to RPM_{MAX_M} may be identified from processed engine data **216**.

FIG. **6** shows an example chart **600** of engine power values and corrected mass flow values contained within processed engine data **216** according to one example embodiment. In the example of FIG. **6**, processed engine data **216** represents only baseline engine data **212**, which may be the case, for example, if the only information available is information provided by the engine manufacturer. In the example of FIG. **6**, the maximum power level obtained during the power sweep (RPM_{MAX_M}) is located somewhere above threshold value **430** and below the overall maximum power level for the engine, RPM_{MAX}.

At step **350** of method **300**, the filter coefficient is generated corresponding to when the maneuver was performed. Returning to the previous example, the filter coefficient for the power sweep may be expressed in the following formula:

$$\Delta P_{MAX_M}=K_{T_M}(Q_{MAX_M})^2,$$

wherein ΔP_{MAX_M} represents the change in pressure across the filter, K_{T_M} is the filter coefficient for the power sweep, and Q_{MAX_M} is the flow determined at step **340**. In this example,

ΔP_{MAX_M} may be determined by identifying the delta-pressure value collected by sensor units **240** corresponding to the time when the maximum power level for the power sweep (RPM_{MAX_M}) was achieved.

At step **360** of method **300**, the flow values achieved over the course of the maneuver are determined. As explained above, the system resistance coefficient may change over time due to degradations in air filter quality but may not necessarily change due to differences in air flow volume. Accordingly, teachings of certain embodiments recognize the capability to use the power sweep filter coefficient, K_{T_M}, to solve for the flow values (Q) achieved across the entire power sweep. These flow values (Q) achieved across the entire power sweep may be expressed in the following formula:

$$\Delta P_n = K_{T_M}(Q_n)^2.$$

In this example, each ΔP_n may be determined by identifying the delta-pressure value collected by sensor units **240** at time n during the power sweep.

If the values for Q_n are known for each point in time n in a power sweep, then these flow values for Q_n may be correlated back to the engine power values RPM_n achieved during the power sweep, as shown in FIG. **5**.

FIG. **7** shows an example table **700** of flow values Q_n and corresponding engine power values RPM_n. In one example embodiment, table **600** may represent an example of engine data updates **214** that may be provided to engine data repository **210** and incorporated into processed engine data **216**. Teachings of certain embodiments recognize that the flow values Q_n obtained through method **200** may be more accurate than the baseline engine data **212** provided by the engine manufacturer, especially for engine power values below threshold value **430**.

Using accurate flow values, the current delta-pressure value corresponding to the overall maximum power level for the engine, RPM_{MAX}, may be determined. For example, FIG. **8** shows a method **800** for determining the current delta-pressure value corresponding to the overall maximum power level for the engine according to one example embodiment. In some embodiments, all or some of the steps of method **800** may be performed by the filter measurement unit **230** of system **200**.

As stated above, the system coefficient may change over time due to degradation in the operating condition of the air filter. Accordingly, in order to determined the current delta-pressure value corresponding to the overall maximum power level for the engine, the current system coefficient is determined at step **810**. The current filter coefficient, K_{T_c}, may be expressed in the following formula:

$$\Delta P_c = K_{T_c}(Q_c)^2.$$

In this example, ΔP_c may represent the current delta-pressure value provided by sensor units **240**, and Q_c may be determined by identifying the flow value in processed engine data **216** corresponding to the current engine power level identified by sensor units **240**.

At step **820**, the overall maximum power value for the engine, RPM_{MAX}, may be determined. In some scenarios, the overall maximum power value for the engine may be provided by the engine manufacturer, as seen in the example graph **600** of FIG. **6**. Once the overall maximum power value for the engine, RPM_{MAX}, is known, the corresponding maximum flow value, Q_{MAX}, may be determined from processed engine data **216**.

At step **830**, the current maximum delta-pressure value for the air filter may be determined. This current maximum delta-pressure value may be expressed by the following formula:

$$\Delta P_{MAX_c} = K_{T_c}(Q_{MAX})^2$$

This current maximum delta-pressure value may represent, among other things, what the delta-pressure value would be if the engine power was increased the maximum engine power level.

Although this example focuses on the maximum delta-pressure value, teachings of certain embodiments recognize the capability to predict the delta-pressure value across a range of engine power levels, flow volumes, and air filter conditions.

Teachings of certain embodiments recognize that methods such as methods **300** and **800** may be performed during operation of a vehicle such as rotorcraft **100**. For example, method **300** continuously identify new maneuvers and add new engine data to the repository. In this example, method **800** may continuously monitor the operating condition of the air filter as both the air filter status and the engine data change over time. In this example, engine flow measurement unit **220** may continuously "learn" how the engine operates, which may result in the delta-pressure predictions provided by filter measurement unit **230** becoming more accurate over time.

Modifications, additions, or omissions may be made to the systems and apparatuses described herein without departing from the scope of the invention. The components of the systems and apparatuses may be integrated or separated. Moreover, the operations of the systems and apparatuses may be performed by more, fewer, or other components. The methods may include more, fewer, or other steps. Additionally, steps may be performed in any suitable order.

Although several embodiments have been illustrated and described in detail, it will be recognized that substitutions and alterations are possible without departing from the spirit and scope of the present invention, as defined by the appended claims.

To aid the Patent Office, and any readers of any patent issued on this application in interpreting the claims appended hereto, applicants wish to note that they do not intend any of the appended claims to invoke paragraph 6 of 35 U.S.C. § 112 as it exists on the date of filing hereof unless the words "means for" or "step for" are explicitly used in the particular claim.

What is claimed is:

1. A filter condition monitoring system, comprising:

an engine data repository configured to store an engine data set comprising a plurality of stored flow values and a plurality of stored engine power values corresponding to the plurality of stored flow values;

one or more sensor units configured to receive, during operation of an aircraft having an engine and an associated air filter with an inlet and an exhaust, a sensed delta-pressure value and a sensed engine power value corresponding to the sensed delta-pressure value, the sensed delta-pressure value representing a difference in pressure between the inlet and the exhaust of the air filter;

a measurement unit configured to:

identify a first flow value corresponding to the sensed engine power value from the engine data repository;

determine a filter coefficient for the filter as a function of the first flow value and the sensed delta-pressure value;

identify a second engine power value from the plurality of stored engine power values and a second flow value corresponding to the second engine power value; and

determine a second delta-pressure value for the air filter as a function of the filter coefficient and the second flow value; and

a filter condition indicator configured to provide an indication representative of the second delta-pressure value.

2. The filter condition monitoring system of claim **1**, the measurement unit comprising a processor configured to determine a maximum delta-pressure value for the air filter and to store the maximum delta-pressure value for the air filter in one or more memory locations associated with the engine data repository.

3. The filter condition monitoring system of claim **1**, wherein:

the second engine power value is a maximum engine power value representing the highest engine power value achievable by the engine; and

the second delta-pressure value is a maximum delta-pressure value representing a prediction for what the delta-pressure value would be if the engine operated at the maximum engine power value.

4. The filter condition monitoring system of claim **1**, wherein the filter condition indicator is an audible or visual alert configured to provide an alert if the second delta-pressure value fails to satisfy a predetermined criterion.

5. The filter condition monitoring system of claim **1**, further comprising a display, wherein the filter condition indicator comprises a visual indication on the display representative of the second delta-pressure value.

6. The filter condition monitoring system of claim **1**, wherein the plurality of stored engine power values comprises power values generic to a category of engines.

7. The filter condition monitoring system of claim **1**, wherein the plurality of stored engine power values comprises a first plurality of power values generic to a category of engines and a second plurality of power values specific to an individual engine.

8. The filter condition monitoring system of claim **1**, further comprising an air filter bypass mechanism configured to bypass the air filter in response to the second delta-pressure value failing to satisfy a predetermined criterion.

9. A rotorcraft, comprising:

a body;

a power train coupled to the body and comprising one or more power sources, a drive shaft coupled to the one or more power sources, and an air filter with an inlet and an exhaust associated with the one or more power sources;

a rotor system coupled to the power train comprising a plurality of rotor blades; and

a filter condition measurement device at least partially disposed within the body, the filter condition measurement device comprising:

an engine data repository configured to store an engine data set comprising a plurality of stored flow values and a plurality of stored engine power values corresponding to the plurality of stored flow values;

one or more sensor units associated with the power train and configured to receive, during operation of the rotorcraft, a sensed delta-pressure value and a sensed engine power value corresponding to the sensed delta-pressure value, the sensed delta-pressure value representing a difference in pressure between the inlet and the exhaust of the air filter;

a measurement unit configured to:

identify a first flow value corresponding to the sensed engine power value from the engine from the engine data repository;

determine a filter coefficient for the filter as a function of the first flow value and the sensed delta-pressure value;

identify a second engine power value from the plurality of stored engine power values and a second flow value corresponding to the second engine power value; and

determine a second delta-pressure value for the air filter as a function of the filter coefficient and the second flow value; and

a filter condition indicator configured to provide an indication representative of the second delta-pressure value.

10. The rotorcraft of claim **9**, wherein the filter condition indicator is an audible or visual alert configured to provide an alert if the second delta-pressure value fails to satisfy a predetermined criterion.

11. The rotorcraft of claim **9**, further comprising a display, wherein the filter condition indicator comprises a visual indication on the display representative of the second delta-pressure value.

12. The rotorcraft of claim **9**, further comprising an air filter bypass mechanism configured to bypass the air filter in response to the second delta-pressure value failing to satisfy a predetermined criterion.

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